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Comets at radio wavelengths

L'étude des comètes en ondes radio

Jacques Crovisier *, Dominique Bockelée-Morvan, Pierre Colom, Nicolas Biver

LÉSIA, Observatoire de Paris, CNRS, UPMC, Université Paris-Diderot, 5, place Jules-Janssen, 92195 Meudon, France

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A B S T R A C T

Comets are considered as the most primitive objects in the Solar System. Their composition provides information on the composition of the primitive solar nebula, 4.6 Gyr ago. The radio domain is a privileged tool to study the composition of cometary ices. Observations of the OH radical at 18 cm wavelength allow us to measure the water production rate. A wealth of molecules (and some of their isotopologues) coming from the sublimation of ices in the nucleus have been identified by observations in the millimetre and submillimetre domains. We present an historical review on radio observations of comets, focusing on the results from our group, and including recent observations with the Nançay radio telescope, the IRAM antennas, the *Odin* satellite, the *Herschel* space observatory, ALMA, and the MIRO instrument aboard the *Rosetta* space probe.

R É S U M É

Les comètes sont considérées comme les vestiges les mieux préservés du système solaire primitif. Leur composition nous renseigne sur la composition de la nébuleuse primitive il y a 4,6 milliards d'années, fournissant des contraintes sur la formation du système solaire. La radioastronomie est un outil privilégié pour l'étude des glaces cométaires. Le domaine décimétrique permet de mesurer la production en eau, par l'observation du radical OH à 18 cm de longueur d'onde. Le domaine millimétrique et submillimétrique permet d'observer de nombreuses molécules provenant de la sublimation des glaces du noyau, ainsi que leurs isotopologues. Nous présentons un panorama historique des découvertes sur les comètes faites en radioastronomie, mettant l'accent sur les résultats de notre groupe, et incluant des observations récentes faites avec le radiotélescope de Nançay, les antennes de l'IRAM, le satellite *Odin*, l'observatoire spatial *Herschel*, ALMA et l'instrument MIRO de la sonde spatiale *Rosetta*.

* Corresponding author.
E-mail addresses: jacques.crovisier@obspm.fr (J. Crovisier), dominique.bockelee@obspm.fr (D. Bockelée-Morvan), pierre.colom@obspm.fr (P. Colom), nicolas.biver@obspm.fr (N. Biver).

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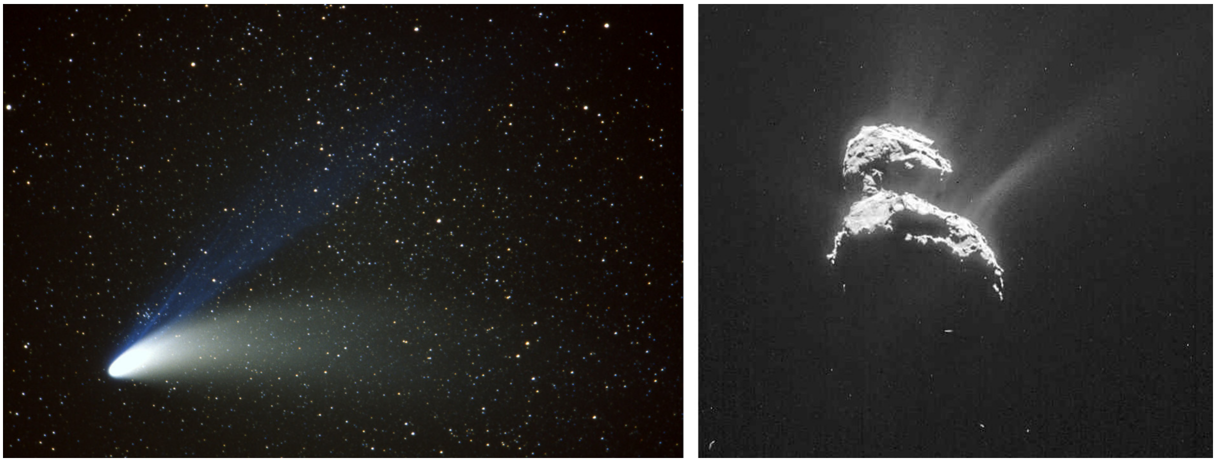

Fig. 1. Cometary images. Left: Comet C/1995 O1 (Hale–Bopp) observed from the Earth on 6 April 1997 (photo: N. Biver). The ion and dust tails are spread here over several 10^7 km (to compare with the Sun–Earth distance 1 AU = 1.5×10^8 km). Right: The nucleus of comet 67P/Churyumov–Gerasimenko observed at a distance of 198 km by the *Rosetta* space probe on 18 February 2015 (©ESA/*Rosetta*/NAVCAM). The size of the nucleus is about 4 km. This image was processed to enhance the dust jets that escape the nucleus.

1. Introduction

With a size of a few kilometres, cometary nuclei are practically unobservable at a distance. Their direct study requires exploration by spacecraft. However, they are icy bodies. When they approach the Sun, ices sublimate, releasing gas and dust, which form an atmosphere and tails that may become very spectacular (Fig. 1). As they contain matter which remained practically intact since the beginning of the formation of the Solar System, these bodies are precious testimonies from the past that justify dedicated studies.

Early in the history of radio astronomy, the first attempts to observe *great comets* C/1956 R1 (Arend–Roland), C/1965 S1 (Ikeya–Seki), C/1969 Y1 (Bennett) and a few others did not yield probing results. Indeed, it is not easy to observe a comet at radio wavelengths. The signal is weak so that large radio telescopes, equipped with sensitive receivers, are needed. The observations should only be attempted on bright comets, which are rare. For these moving objects, one must blindly rely on ephemerides and the telescope tracking system. Last but not least, comets are variable, unpredictable objects, so that an observation can difficultly be repeated for confirmation. It is thus not a surprise that the beginnings of the radio investigation of comets were a succession of failures, missed opportunities, contradictory results and doubtful detections that could not be confirmed.

2. 1973: comet Kohoutek

At the end of 1973, the NASA organized a worldwide campaign to observe comet C/1973 E1 (Kohoutek), in support to its observation aboard the Skylab orbital station. Following this opportunity, the observation of the OH radical lines at 18-cm wavelength was attempted at Nançay. Their detection was the first detection of a comet at radio wavelengths (Fig. 2, [1,2]).

The OH radical is a photodissociation product of water, the major constituent of cometary ices. Its observation allows one to determine the production rate of water, and thus to quantify the activity of the comet. This observation of comet Kohoutek was the beginning of a programme of systematic observations, which is still ongoing at the Nançay radio telescope. More than 130 comets were thus observed. The evolution of their activity was followed, in some cases over many months, to prepare or to complement their observations with other instruments.

3. 1986: Halley's comet

The historic and mythical Halley's comet (1P/Halley) was in 1986 the target of a space exploration by no less than five spacecraft. Its observation from the Earth was also the topic of an international supporting campaign advocated by the *International Halley Watch*. The radio aspects of this campaign [4] were coordinated by Éric Gérard (France), William Irvine, and F. Peter Schloerb (United States).

The OH 18-cm lines in Halley's comet have been monitored with the Nançay radio telescope for a year and a half in 1985–1986 and with several other telescopes [3,4]. The same lines were also mapped with the Very Large Array (VLA) interferometer [5]. Hydrogen cyanide (HCN) was detected by the newly commissioned 30-m radio telescope of IRAM ("Institut de radio astronomie millimétrique") at Pico Veleta (Spain) (Fig. 3, [6]).

This marked the entry of cometary radio astronomy in the world of molecular radio spectroscopy, already so successful in the study of interstellar molecules. A short time after came the identification, still at IRAM, of methanol (CH_3OH) and hydrogen sulphide (H_2S) in comets C/1989 X1 (Austin) and C/1990 K1 (Levy) [7].

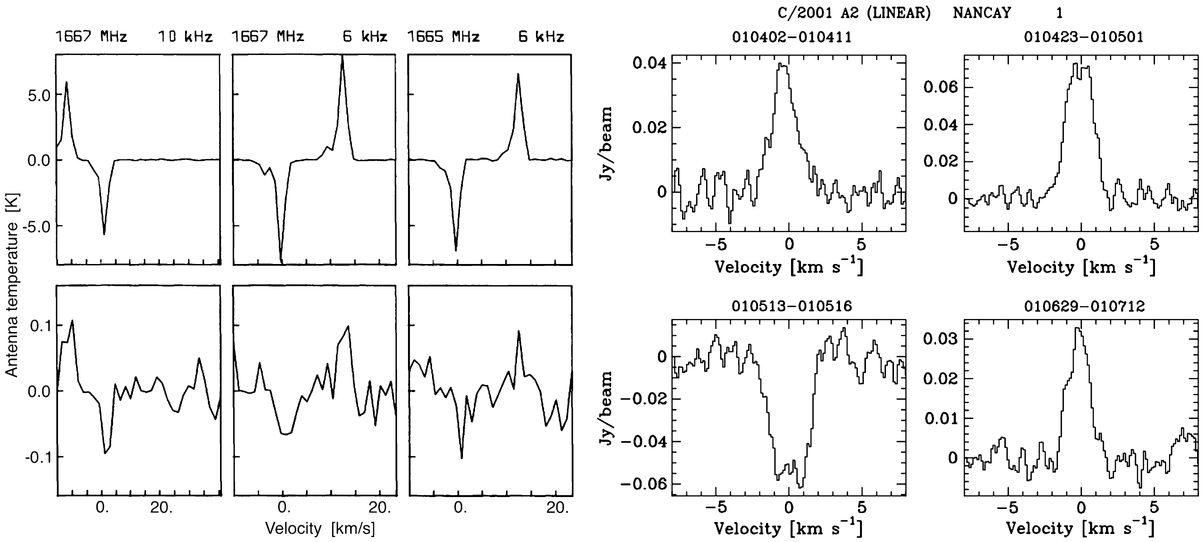

Fig. 2. OH spectra from Nançay. Left: Spectra showing the detection of the OH lines at 18 cm for the first time in a comet, C/1973 E1 (Kohoutek), in December 1973 with the Nançay radio telescope [1]. The upper panels show for comparison the OH lines observed in absorption in the galactic source W12. The lower panels show the same lines observed from 1 to 12 December in the comet. The observations were performed with frequency switching so that a positive and negative signal pattern appears. Right: A selection of OH spectra obtained at Nançay in comet C/2001 A2 (LINEAR) from April to July 2001 [3]. Depending on the date, the excitation conditions change and the line appears in emission or in absorption. In this figure as in most of the spectra shown in this article, the frequency scale of the *x*-axis has been converted into velocities in the frame of the comet following the Doppler law. The intensity scales, as is usual in radio astronomy, are given as antenna temperature or brightness temperature in units of kelvins, which is the equivalent temperature of a black body in the Rayleigh–Jean approximation, or flux density in units of janskys (1 Jy $= 10^{-26}$ W·m^{-2}·Hz^{-1}).

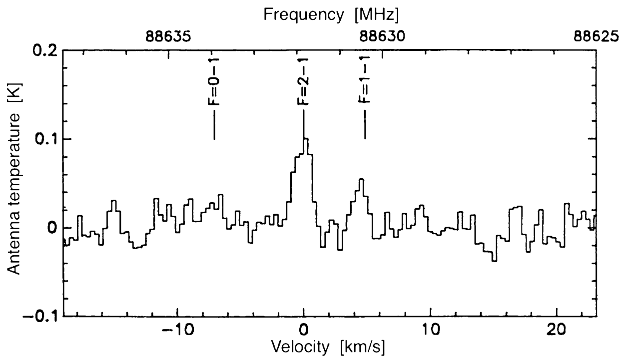

Fig. 3. The detection of the three hyperfine components of the J 1–0 rotational line at 88.6 GHz of hydrogen cyanide HCN in Halley's comet with the 30-m antenna of IRAM in November 1985 [6].

4. 1997: comet Hale–Bopp

Another exceptional comet was giant comet C/1995 O1 (Hale–Bopp). Its early discovery, one year and 8 months before its perihelion passage on 1st April 1997, favoured the organization of its observing campaign. It could be detected at Nançay at the record distance of 4.6 AU from the Sun. Its water production rate reached at perihelion 300 tons per second, 10 times more than Halley's comet. The monitoring of the OH production served as a reference for the other molecular radio observations (Fig. 4).

It is remarkable that among the two dozens of molecular species released by cometary ices which were then identified in this comet, two-third were identified by radio spectroscopy (Figs. 4, 5, [8–10]). In addition to carbon monoxide, one can note:

– CHO molecules: H_2CO, CH_3OH, HCOOH, $HCOOCH_3$, $(CH_2OH)_2$;
– nitrogenous molecules: NH_3, HCN, HNC, HC_3N, CH_3CN, NH_2CHO;
– sulphuretted molecules: H_2S, CS, SO, SO_2, OCS, H_2CS.

In addition, isotopic ratios D/H, $^{12}C/^{13}C$, $^{14}N/^{15}N$, $^{32}S/^{34}S$ were also measured. Most of these detections were made at millimetric or submillimetric wavelengths with the IRAM radio telescopes (the 30-m antenna in Spain and the interferom-

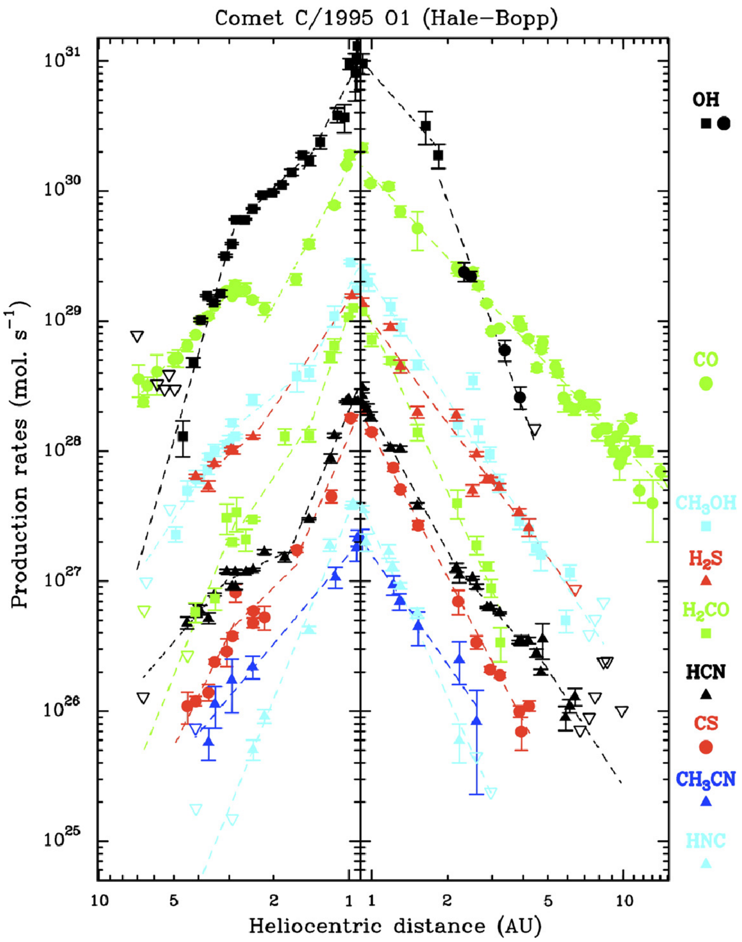

Fig. 4. Evolution of the production rates of various molecules in comet C/1995 O1 (Hale–Bopp) as a function of its distance to the Sun [8]. The left part refers to the pre-perihelion period, with the comet approaching the Sun, and the right part, to the post perihelion period, with the comet receding from the Sun. The data for the OH radical, which traces water production, are from Nançay (squares), with additional post-perihelion values from UV observations (circles). The other molecules were observed with the IRAM 30-m antenna (Spain) or the SEST 15-m telescope (Chile). Downward-pointing triangles are upper limits. Water sublimation appears to be the dominant process at less than 3 AU from the Sun, whereas carbon monoxide could be responsible for cometary activity at larger distances. The asymmetry of the curves may be due to season effects, or to thermal evolution of the cometary nucleus.

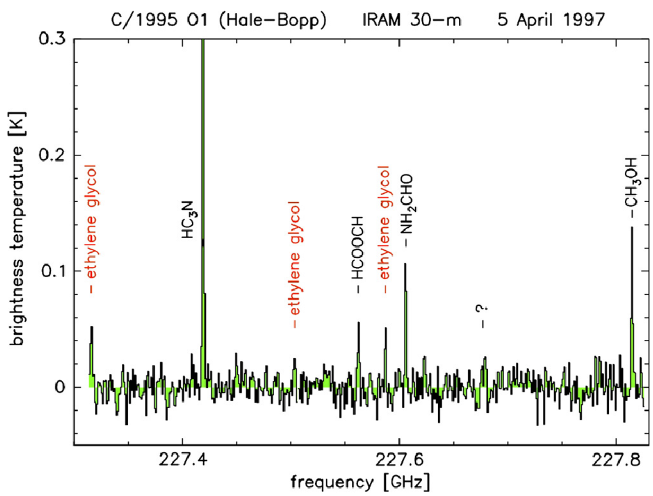

Fig. 5. A spectrum of comet C/1995 O1 (Hale–Bopp) observed with the IRAM 30-m antenna, showing the lines of several complex organic molecules [10]. The lines of ethylene glycol $(CH_2OH)_2$ were identified seven years after the observation, following the publication of the laboratory spectrum of this molecule.

eter at Plateau-de-Bure), the CSO (Caltech Submillimeter Observatory 10.5-m antenna) and the JCMT (James Clerk Maxwell Telescope 15-m antenna) at Hawaii. Ammonia was detected at centimetric wavelengths with the 100-m radio telescope at Effelsberg (Germany) [11]. Other molecules, which are non-polar, and thus devoid of rotational lines at radio wavelengths, were detected by infrared spectroscopy: carbon dioxide, and the hydrocarbons CH_4, C_2H_2, C_2H_6. Another wealth of identifications of cometary molecules is expected from the in situ investigations of the mass spectrometers aboard *Rosetta*.

Radio observations also allow us to probe key physical parameters of the cometary atmosphere:

– its expansion velocity, from the shapes of the lines, taking advantage of the very good spectral resolution of the radio technique;
– its temperature, from the simultaneous observation of the intensity of several rotational lines of a molecule such as methanol.

For comet Hale–Bopp, it was possible to follow the evolution of these parameters over a large range of heliocentric distances (up to 14 AU; Fig. 4). The coma expansion velocity was observed to increase from 0.5 to 1.3 km/s, and the temperature from about 20 K to 130 K, as the comet approached the Sun. These variations are in agreement with thermodynamical models of the coma.

5. Recent observations at IRAM and with ALMA

The versatility of the spectrometers now equipping the IRAM 30-m radio telescope is precious for cometary observations, which are time-critical and which cannot be easily repeated. With an instantaneous frequency coverage of 2×8 GHz, spectral surveys are now easily feasible, allowing simultaneous observations of many molecules and serendipitous detections. In recent comets C/2012 F6 (Lemmon) and C/2013 R1 (Lovejoy), this possibility allowed us to retrieve some molecules which up to now were only spotted in comet Hale–Bopp [12]. And in comet C/2014 Q2 (Lovejoy), two new molecules – ethanol (C_2H_5OH) and glycolaldehyde (CH_2OHCHO) – were detected in January 2015 [13].

Continuum emission as well as molecular line emissions can be mapped by radio interferometers. The cometary continuum is dominated by the thermal emission of dust in the coma, the signal from the nucleus being very difficult to detect with Earth-based observations, except for comets coming close to the Earth. Continuum emission from dust particles is only significant at wavelengths smaller than the particle size. Thus its observation at millimetric wavelengths characterizes large-size particles. This is complementary to visible and infrared observations, which are sensitive to particles of very small sizes.

Mapping molecular lines allows us to know the distribution of these molecules within the coma and to probe coma chemistry. The origin of the gas molecules may thus be traced: they are either coming directly from the nucleus, or progressively injected in the coma following chemical reactions or the sublimation of icy grains. Asymmetries in their distribution may be due to *jets* originating from *active regions* of the nucleus' surface.

The IRAM interferometer at Plateau-de-Bure consists presently of six 15-m antennas, which are to be extended to 12 antennas with the NOEMA (NOrthern Extended Millimetre Array) project. Its first significant results were obtained on comet Hale–Bopp in 1997 [14,15], then at the occasion of the outburst of comet 17P/Holmes [16] and of the passage close to the Earth of comet 107P/Hartley 2 (Fig. 6, [17]). The Atacama Large Millimeter/submillimeter Array (ALMA) in Chile, with its 50 12-m antennas, is more sensitive. Its first cometary observations were performed in 2013 on comets C/2012 F6 (Lemmon) and C/2012 S1 (ISON). (Fig. 7, [18].)

6. Space radio telescopes: *SWAS*, *Odin*, *Herschel*

Although water is the prime constituent of cometary ices, its observation is difficult. Its rotational lines, which are in the submillimetre range, are not observable from the ground due to the opacity of the Earth's atmosphere. Their detection in comets is relatively recent.

The fundamental submillimetric line of water at 557 GHz (the 1_{10}–1_{01} transition at 0.5 mm wavelength) was finally observed from two satellites dedicated to the study of this line, the Submillimeter Wave Astronomy Satellite (*SWAS*, launched by the United States in 1998), and *Odin* (launched by the Swedish space agency in 2001, with a French participation consisting in the delivery of an acousto-optic spectrometer). *Odin* observed water in a dozen of comets. It also observed NH_3 and $H_2^{18}O$, measuring for the first time by remote sensing the $^{18}O/^{16}O$ isotopic ratio in a comet. *Odin* is still operational and observed comet C/2014 Q2 (Lovejoy) in February 2015. (Fig. 8, [19,20].)

The next step was the *Herschel* space observatory, operating in the submillimeter and far-infrared domains, launched by the European Space Agency. With its 3-m diameter mirror and its liquid-helium-cooled instruments (including HIFI, the Heterodyne Instrument for the Far Infrared), it was much more sensitive than its predecessors. From 2009 to 2013, it could study and map several lines of water in a dozen of comets, some of them being weak, distant comets. In three of them, it measured the D/H isotopic ratio. (Figs. 9, 12 [21–23].)

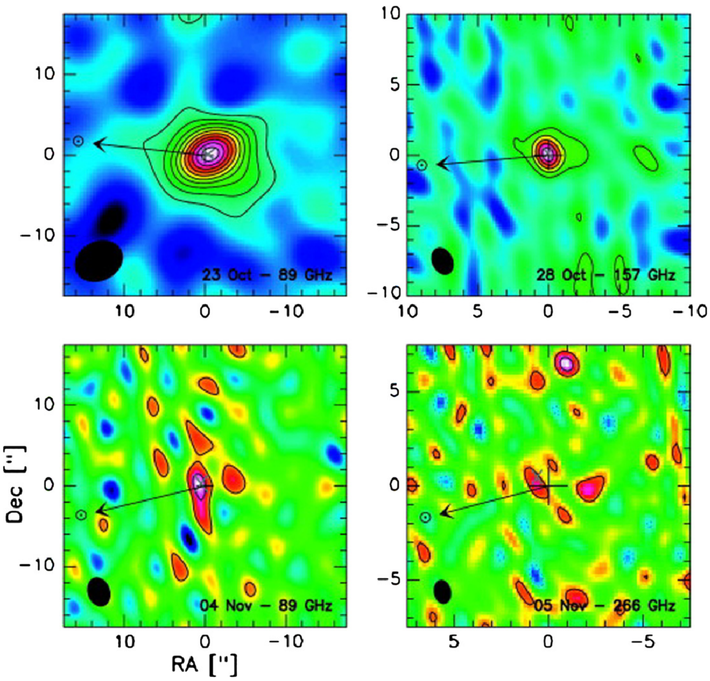

Fig. 6. Maps of continuum emission at 1, 1.5 and 3 mm wavelength of comet 103P/Hartley 2 observed with the IRAM interferometer at Plateau-de-Bure in October–November 2010 [17], when this comet passed at only 0.12 AU (1.8×10^7 km) from the Earth. These maps show the distribution of large-size dust particles in the coma and the continuum emission of the nucleus. The arrows show the direction of the Sun.

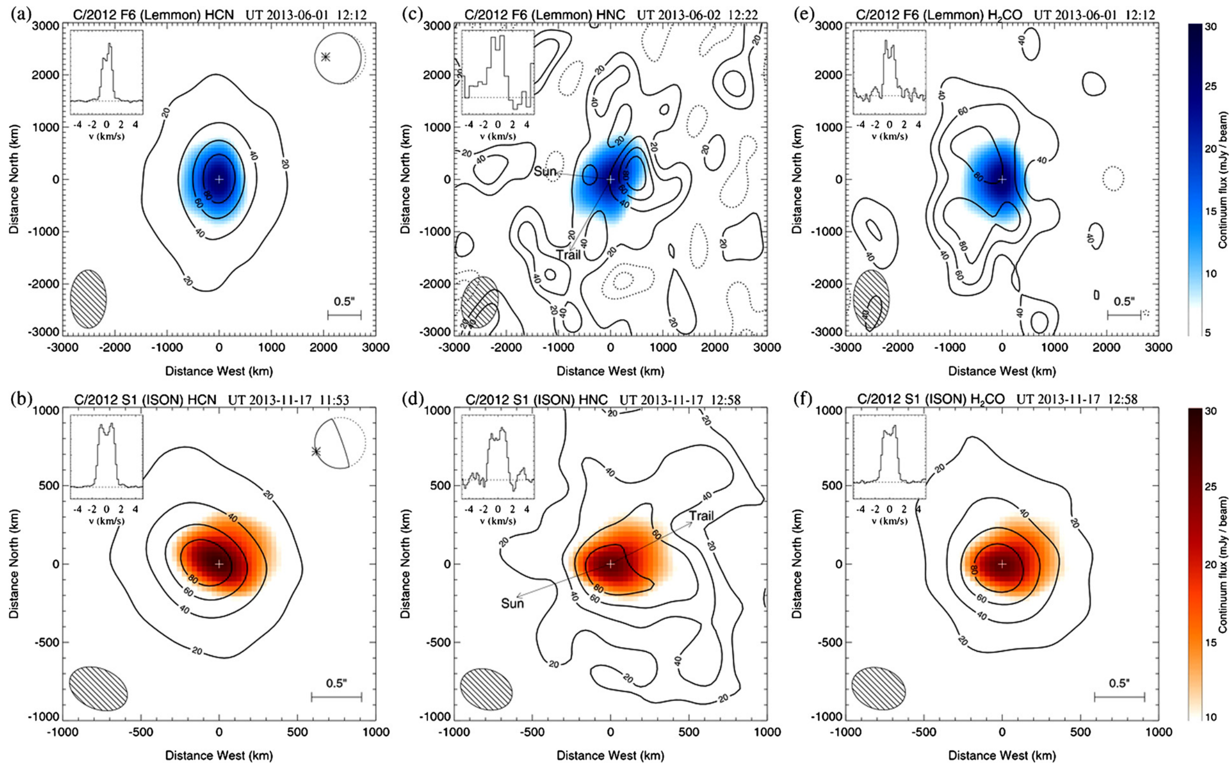

Fig. 7. From left to right, maps of the emission lines of hydrogen cyanide HCN, its isomer HNC and formaldehyde H_2CO observed with ALMA in comets C/2012 F6 (Lemmon) (top) and C/2012 S1 (ISON) (bottom) [18]. The spectra of the individual lines are shown in the upper left inserts. These maps show that molecules such as HNC and H_2CO are progressively released in the coma from still ill-known sources, whereas HCN seems to come directly from the nucleus ices.

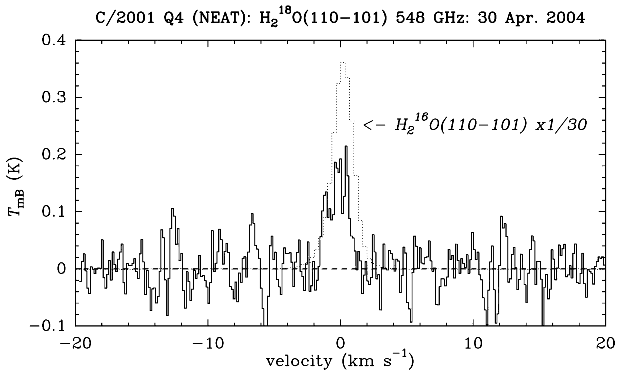

Fig. 8. The water lines of the water isotopologues $H_2^{16}O$ and $H_2^{18}O$ observed by the *Odin* satellite in comet C/2001 Q4 (NEAT) [20].

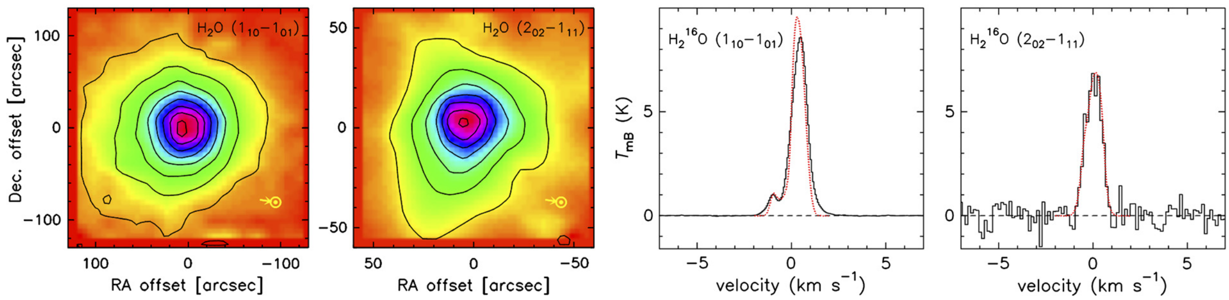

Fig. 9. Maps and profiles of water lines in comet C/2009 P1 (Garradd) observed with the *Herschel* space observatory [23]. The 1_{10}–1_{01} line at 557 GHz is not symmetric: this very strong line is saturated, showing an indentation at negative velocities caused by self-absorption from the foreground external layers of the cometary atmosphere.

7. Close observation of a comet with MIRO, the radio telescope aboard *Rosetta*

The *Rosetta* space probe, launched by the European Space Agency in 2004, explored comet 67P/Churyumov–Gerasimenko, orbiting its nucleus at distances which, at some moments, were as close as 8 km. It was equipped with a dozen of instruments, one of them being MIRO (Microwave Instrument for the *Rosetta* Orbiter), a radio telescope with an antenna of only 30 cm diameter. In the vicinity of the comet, this modest size is enough to study a selection of lines of water (several isotopic species), methanol, ammonia and carbon monoxide with a spectrometer operating around 0.5 mm wavelength. MIRO is also equipped with two continuum channels at 0.5 and 1.6 mm wavelength, dedicated to the observation of the thermal emission of the nucleus (Figs. 10, 11, [24,25]).

Rosetta and its instruments were to monitor the evolution of the comet until the end of September 2016 and to follow its activity, which climaxed at its perihelion in August 2015.

8. Other studies and perspective

This rapid survey, mainly focused on the results from our group, is far from exhausting all aspects of the study of comets at radio wavelengths. One should also mention:

- Continuum observations with bolometers on single dish telescopes, sensitive to dust grains in the coma [26].
- Radar studies of cometary nuclei, which determine the size and shape of these objects when they come within the range of large Earth-based antennas [27];
- The study of the plasma environment of comets, where the solar wind and the cometary coma interact [28];
- The velocimetry of cometary space probes, still the only way to evaluate precisely the mass of cometary nuclei. Compared with the nucleus dimensions obtained by imaging, the nucleus density can then be obtained. *Rosetta* thus determined a density of 533 kg·m^{-3} for 67P/Churyumov–Gerasimenko [29];
- The tomography of the nucleus of 67P/Churyumov–Gerasimenko performed by the CONSERT instrument, a bi-static radar operating between the *Rosetta* orbiter and its lander Philae [30];
- Laboratory measurements of cometary matter analogues, for the interpretation of radar and radiometric observations of cometary nuclei [31].

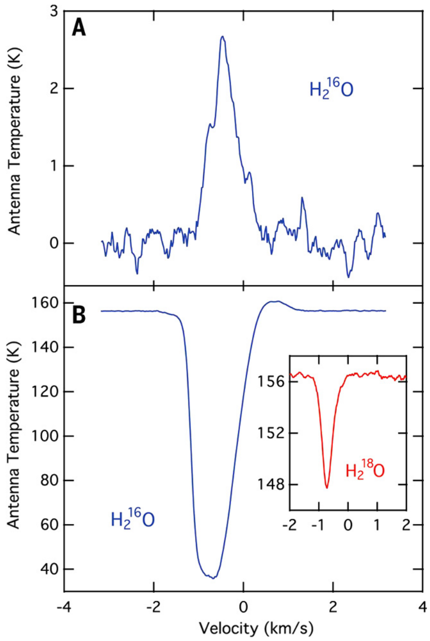

Fig. 10. An example of the water lines observed at 0.5 mm wavelength in comet 67P/Churyumov–Gerasimenko with MIRO on *Rosetta* [25]. Top: observation on 23 June 2014 at a distance of 128 000 km. Bottom: observation on 19 August 2014 at a distance of 81 km; the lines are then seen in absorption against the continuum of the nucleus.

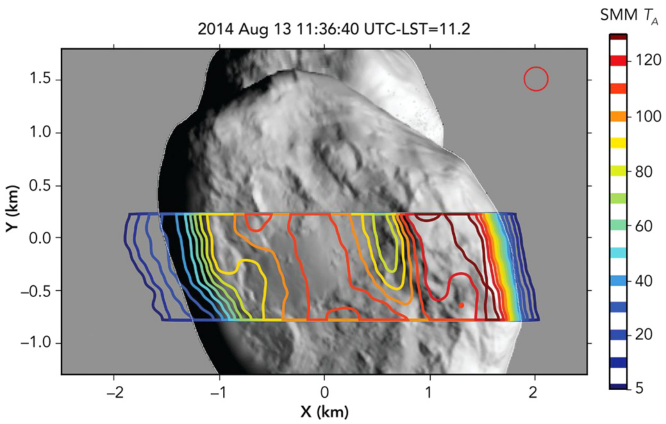

Fig. 11. A partial map of the temperature of the nucleus of comet 67P/Churyumov–Gerasimenko, from the submillimetric continuum observations of MIRO on *Rosetta*, superimposed on the model of its shape deduced from imaging in the visible [25]. It can be seen on the left side that MIRO observes the night side, for which visible imaging provides no information. The temperatures vary, following solar insolation, from about 30 K (night side) to 130 K. The comet was then at 3,5 AU from the Sun.

The space exploration of comets, due to its complexity and its high cost, will be limited for a long time to a small number of targets, which precludes statistical investigations. These latter can only be done from Earth-based systematic observations. The observations of several tens of comets, and especially spectroscopic radio observations, have shown that the relative productions of water, carbon monoxide, methanol, and many other molecular species may highly differ from one object to the other. This suggests that comets have different chemical compositions, but we do not know yet how these differences are related to the history of the formation and evolution of these bodies.

The D/H isotopic ratio of cometary water, compared to that of Earth oceans, is customarily used to test the hypothesis of a cometary origin for terrestrial water. This ratio is presently only known for a small number of comets (from radio observations for several of them). These D/H values range from one to three times the terrestrial value, which seems to rule out an origin from only comets (Fig. 12, [22,23,32]). In the future, a better knowledge of this statistic will help us to better know to which extent the fall of comets, asteroids and other small bodies on Earth contributed to terrestrial water. Further constraints on the origin of comets and cometary material are also provided from the D/H and other isotopic ratios that are measured in molecules other than water.

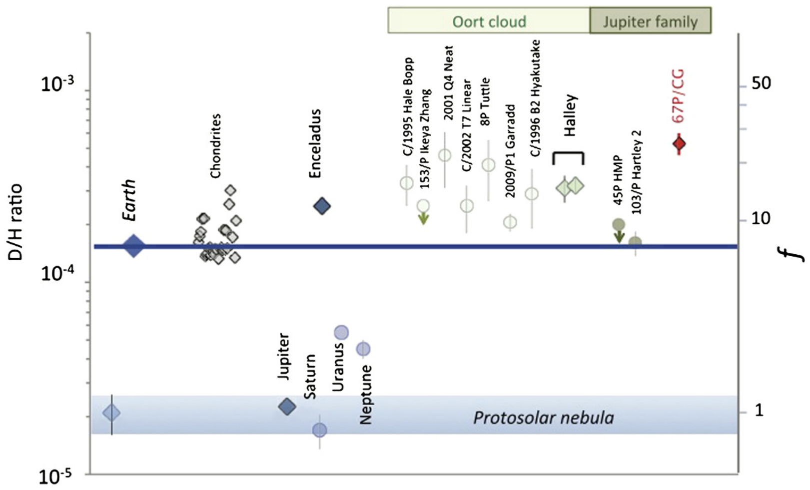

Fig. 12. The D/H ratio observed in cometary water and in other Solar System bodies. Most of the cometary data are from radio observations. The cometary D/H ratio ranges from one (103P/Hartley 2 observed with *Herschel*) to three times (67P/Churyumov–Gerasimenko observed with the ROSINA mass spectrometer of *Rosetta*) its value in Earth oceans [22,23,32].

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